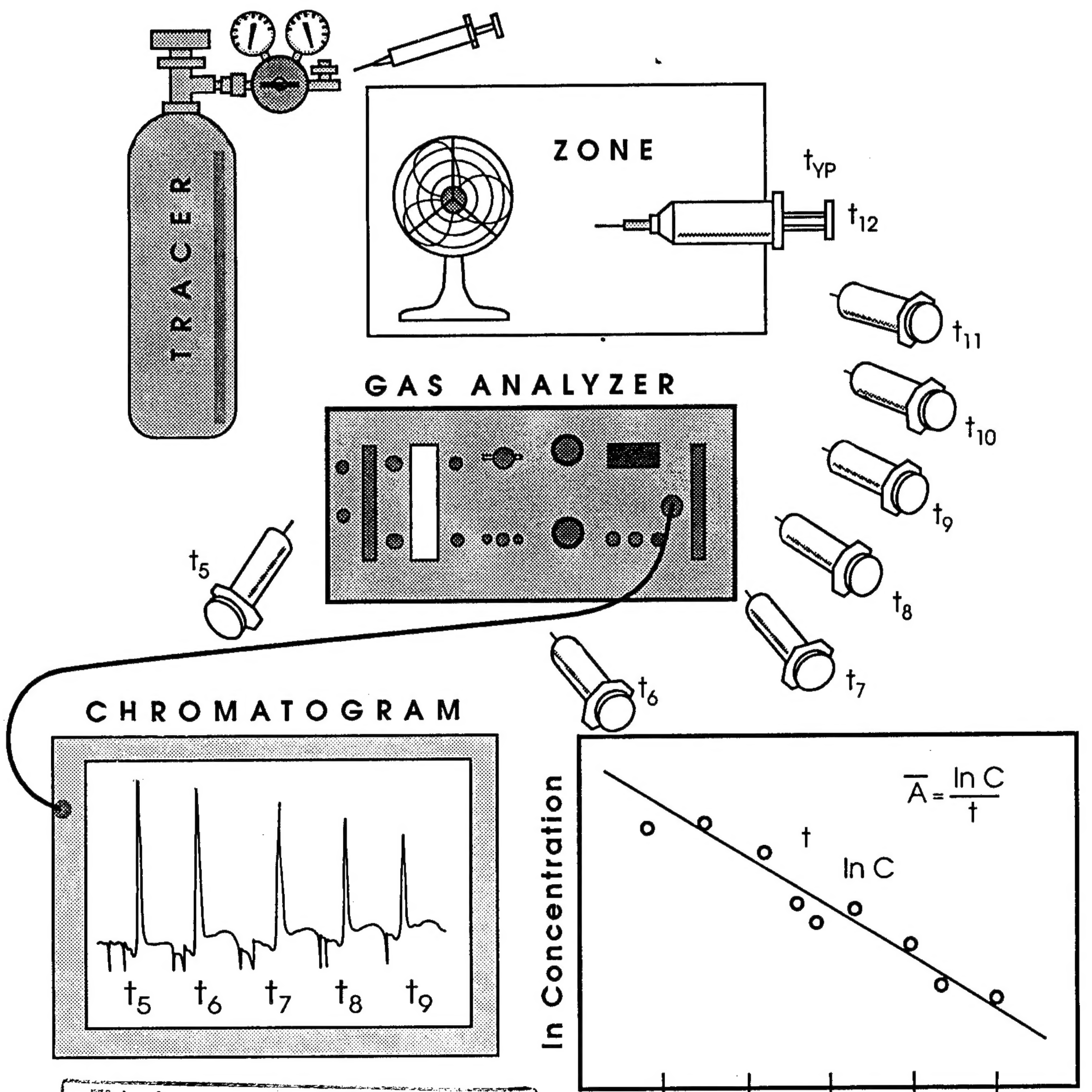
CRREL REPORT 94-8

CRREL

Air Exchange Measurements in Army Buildings

Stephen N. Flanders

July 1994



Abstract

Air exchange measurements in buildings are important for testing the effectiveness of the ventilation system and for characterizing air leakage in the building envelope when the ventilation is off. This report discusses such measurements in nine Army buildings—administrative, maintenance, barracks, hospital and laboratory buildings—using a tracer gas method that entails releasing a tracer gas in an initial well-mixed concentration and then monitoring its concentration over time. The faster the tracer gas dilutes, the greater is the air change rate. ASTM Standard E741 offers techniques for tracer gas measurements in single-zone enclosures, but most Army buildings are multiple-zone enclosures. This study, looking at whether such buildings could approximate single-zone enclosures for tracer gas measurements, found that this is difficult. In addition, a number of buildings were detected in which the mechanical ventilation system was working at a fraction of design capacity.

Cover: Tracer gas dilution technique for measuring air exchange rates.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380-89a, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

CRREL Report 94-8

US Army Corps
of Engineers
Cold Regions Research &
Engineering Laboratory

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PREFACE

This report was prepared by Stephen N. Flanders, Research Civil Engineer, Civil and Geotechnical Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. This report results from research performed under DA Project 4A752784AT42, Budget Package, *Installation Operations;* Work Package, *DEH Management;* Work Unit BS018, *Advanced Diagnostic Techniques for Military Building Envelopes in Cold Regions.*

The author thanks the following people and organizations: Dr. Andrew K. Persily of the National Institute for Standards and Technology and Michael Kemme of the Construction Engineering Research Laboratory, for their technical reviews of this report; Mark Hardenberg, CRREL, for his editorial assistance; Stephen Rowley of the Directorate of Engineering and Housing (DEH) at Fort Drum, and people at the DEH organizations at Fort Wainwright and Fort Richardson who provided facilities and coordination for this study.

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STEPHEN N. FLANDERS

INTRODUCTION

Why measure air exchange?

Air exchange measurements are significant to building designers and operators who wish to know whether an existing building is providing insufficient or too much ventilation, or the extent to which the building envelope is responsible for air exchange. We may do such measurements with a mechanical ventilation system in operation or under conditions of natural air exchange. In this report, air exchange is measured as an air change rate, which is defined below. This report is about the use of the tracer gas decay technique to measure air exchange in a variety of Army buildings to determine the extent to which the technique applies to Army building types.

About the techniques

Tracer gas dilution

The measurement principle employed in this report is tracer gas dilution, standardized in E741 (ASTM 1990). A readily measurable tracer gas is distributed uniformly in the building. The measurement of the concentration, and sometimes the volume rate (volume/time), of the tracer gas that is injected into the zone allows calculation of the volume rate of air flowing out of the zone. This measurement pertains solely to the prevailing conditions of building operation and weather conditions. It characterizes the air change rate of the building at that time, not the tightness of the envelope or some equivalent fixed, physical quantity.

E741 (ASTM 1990) presents three techniques—concentration decay, constant injection and constant concentration. The latter two techniques require a substantial tracer gas distribution apparatus. They determine air change flow, that is the total volume of air passing through the zone to and from the outdoors in units of cubic meters per hour (m^3/h). Experience with these techniques is widely reported, for example in Harrje et al. (1990).

The concentration decay technique has simpler apparatus requirements than the other two. It uses the rate at which the tracer gas' concentration decays to determine the air change rate of the zone, the ratio of the total volume of air passing through the zone to and from the outdoors per unit of time to the volume of the zone in units of $hours^{-1}$ (also commonly called "air changes per hour" or ACH). The *Methodology* section describes this technique more fully.

Fan pressurization

A related measurement technique, using fan pressurization, characterizes the tightness of a building envelope, but does not by itself predict the building's air exchange behavior under various operating and weather conditions. This technique, which is discussed widely in the literature, was the subject of CRREL Report 92-2 (Flanders 1992), and is standardized in E779 (ASTM 1987).

About the buildings

Army buildings

The operating budgets of most Army bases preclude many buildings from receiving more than minimal maintenance. Consequently, we do not know readily which buildings are wasting energy or providing inadequate ventilation to their inhabitants. This study explores the feasibility of using tracer gas dilution as a technique to determine adequate or excessive air exchange rates in Army buildings.

Building types

Army buildings in Alaska were the focus of air change measurements in a previous study (Flanders 1990). The buildings included in this study are a

laboratory building, an administrative building, a barracks, a bowling alley, portions of a hospital and a social club. This type of measurement was also used in three different motor vehicle and aircraft maintenance facilities. The buildings included in this study do not purport to represent the Army's building stock, as a whole, but do offer instructive lessons about the possibilities for and problems with such measurements in a variety of building types.

Building venues

The buildings tested were 1) the CRREL laboratory addition in Hanover, New Hampshire, 2) building P4070, an administrative building at Fort Wainwright, Alaska, near Fairbanks, 3) building 666, a barracks at Fort Richardson, Alaska, near Anchorage, 4) the operating, delivery and nursery suites in Bassett Army Hospital at Fort Wainwright, 5) building P3702, the bowling alley at Fort Wainwright, 6) the Junior Enlisted Club at Fort Wainwright, which was under construction at the time, 7) building 3105, the Directorate of Engineering and Housing shop at Fort Wainwright, 8) building P10670, the unit motor vehicle maintenance building at Fort Drum, and 9) building P2050, the aviation maintenance and overhaul building at Fort Drum.

METHODOLOGY

Assumptions

Single-zone idealization

Most buildings are made up of multiple compartmented areas that constitute zones. In such cases, it is difficult to determine whether air flowing into a zone is from the outdoors and tracer-gas free or from an another zone and bears tracer gas. For these experiments, each building was idealized as a single zone. The appropriateness of that idealization was then examined.

Tracer gas injection

A tracer gas should be nontoxic, nonreactive, nonabsorptive and exist only at trace background levels. If the tracer gas concentration can be maintained essentially uniformly throughout the zone, then any change represents the introduction of air from outdoors. Proportionate distribution and good mixing of tracer gas help achieve this uniform concentration and assure that the building behaves as a single zone.

Spatial and time-series gas sampling

Spatial sampling of tracer gas concentrations is necessary to determine whether the single-zone assumption is valid. The tracer gas concentration decay technique requires that we obtain samples at a minimum of two separate times to determine the average decay rate. If we wish to determine whether the decay rate is approximately constant, then sufficient concentration sampling times are needed to perform a linear regression.

Tracer gas concentration measurement

Analysis of an air sample containing tracer gas in a gas analyzer typically produces a nonlinear output response that is a function of tracer gas concentration. The analyzer must be calibrated to establish that response, using carefully prepared calibration gases of standard concentrations. The concentration decay technique does not require absolute accuracy, but only requires that measured concentrations be in correct proportion to one another.

Procedure

Tracer gas injection

E741 suggests that natural convection will cause essentially uniform mixing of the tracer gas throughout the building after about 30 minutes. Use of the building's fan system or other fans also aids mixing. This study used either natural convection or the building's fan system or a combination of both.

Spatial and time-series gas sampling

This study employed automated syringe samplers. Each sampler was set to take twelve 30-cm^3 air samples in sequence, each sampling programmed to be between 5 and 20 minutes long. Sometimes the sampling started when the tracer gas was released, in order to observe the process of tracer gas mixing, and sometimes it started 30 minutes after the release of the tracer gas, when mixing was assumed to be adequate.

To provide spatial sampling as a check for uniform tracer gas concentration, as many as seven automated syringe samplers were placed at widely separated locations in a building. Each floor would receive at least one sampler. When possible, a return air duct would receive a sampler to determine whether the average of the spatial samples of tracer gas concentration agreed with the tracer gas concentration obtained in the return air. The samplers were programmed to sample simultaneously, that is, each

of the 12 syringes would be sampling at precisely the same time as its cohorts in other samplers.

Tracer gas concentration measurement

The gas analyzer used in these studies is an electron-capture gas chromatograph, capable of detecting sulphur hexaflouride (SF_6) in concentrations ranging from 10^{-12} to 10^{-9}. Sulphur hexaflouride meets the criteria for tracer gases laid out above. The small target initial concentrations allow the use of a small syringe, often with between 4 and 15 cm^3 of SF_6, for injection of tracer gas throughout the building. Before use, a calibration standard tracer gas was injected into the chromatograph to determine the repeatability of measurements. In all cases reported, the repeatability was within the 3% coefficient of variation specified by the manufacturer.

The 30-cm^3 air samples were injected into the gas chromatograph 10 cm^3 at a time. The three samples provided redundancy, in case of a mistake and, occasionally, to provide an estimate of the precision of the concentration analysis. The concentrations, together with the time and location that they represented, were recorded in a computer spread sheet.

Analysis

Tracer gas uniformity of distribution

We may test the assumption that the building may be idealized as a single zone by determining the extent that the tracer gas concentration is uniform throughout the building. We may simply determine the coefficient of variation of the tracer gas concentrations of the samples obtained at each time interval. As a visualization, we may plot

$$C_{\text{normal}} \equiv \frac{C_{\text{mean}} - C_{\text{location}}}{C_{\text{mean}}} \quad (1)$$

where C = tracer gas concentration.

We may also compare the bias between the computed average of tracer gas concentrations from the spatially representative samples and the physical average obtained in the return air plenum at each time interval

$$C_{\text{bias}} \equiv \frac{C_{\text{mean}} - C_{\text{return air}}}{C_{\text{mean}}}. \quad (2)$$

Tracer gas concentration decay rate

The general formula for tracer gas change in a single zone is

$$\overline{Q} = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \frac{q_g(t)}{C(t)}\, dt + \frac{V}{(t_2 - t_1)} \ln\left(\frac{C_1}{C_2}\right) \quad (3)$$

where $\overline{Q}$ = average air change flow in the zone (m^3/h)
C= concentration (dimensionless)
V = volume of the zone (m^3)
t = time (h)
$q_g(t)$ = racer gas flow in the zone (m^3/h)
subscripts 1 and 2 equal beginning and ending, respectively.

The tracer gas decay represents a special case where the tracer gas was injected before the samples were obtained, that is $q_g(t) = 0$. Therefore, the air change rate may be calculated as

$$\overline{A} = \frac{\overline{Q}}{V} = \frac{1}{(t_2 - t_1)} \ln\left(\frac{C_1}{C_2}\right). \quad (4)$$

Test for steady-state air exchange

With multiple measurements of $C(t)$ over time, we may test the hypothesis that the air change rate is constant by rearranging eq 4 and performing a regression on

$$\ln C_2 = \ln C_1 - \overline{A} \cdot t. \quad (5)$$

Precision and accuracy

Possible errors associated with these measurements include: 1) inappropriately idealizing a multizone building as a single zone with uniformly distributed tracer gas, 2) assuming that the air change rate is constant, and 3) determining the precision and bias of tracer gas concentration measurement.

The assumption that a building constitutes a single zone implies that $C(t)$ is essentially uniform throughout the building at any time during the measurement. We determine the validity of the single-zone assumption by the coefficient of variation of C_{normal} discussed above. A coefficient of variation of 10% or better helps assure that the calculation of $\overline{A}$ (eq 4) is within 10% of its true value.

The question of gas concentration measurement precision and accuracy does not figure strongly in this measurement. The gas analyzer was tested with a tracer gas standard diluted to different fractions of full strength. This showed a linear relationship between tracer gas concentration and calibrated instrument response. The tracer gas decay method re-

quires only that concentration measurements be correct relative to each other.

FIELD STUDIES

CRREL laboratory addition

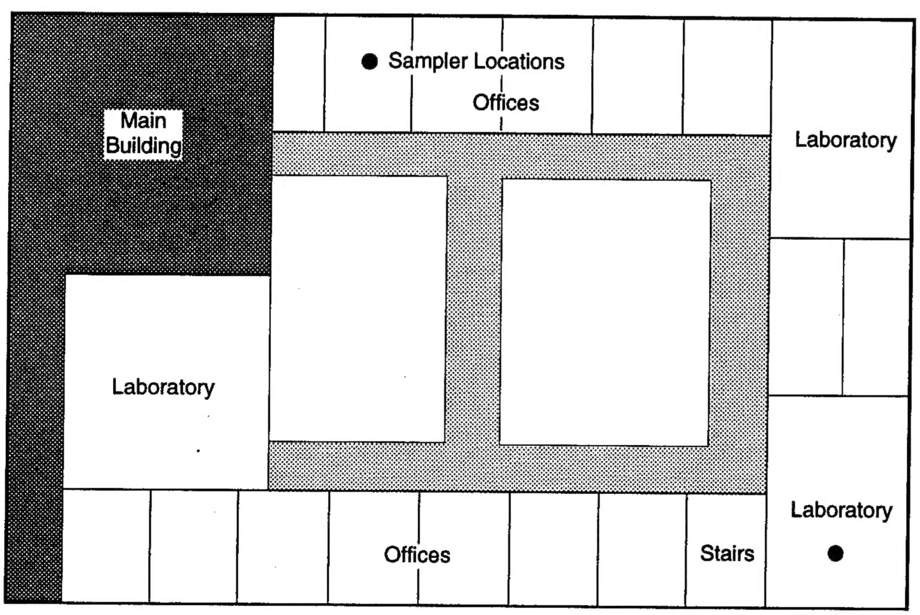
Building

The CRREL laboratory addition has a steel frame with metal stud infill and an exterior cladding of brick veneer. It is mechanically ventilated and air-conditioned and it abuts the original laboratory, a naturally ventilated building. The connection between the buildings is by fire doors leading into a stair well. The laboratory addition has four stories, including a basement and a subbasement. It contains office space and chemical laboratories on the first floor (Fig. 1a).

Zones

The HVAC system comprises separate hot and cold air distribution systems (decks). Each deck has a supply air fan with dampers to control the fraction of fresh air introduced into the system with the return air. Both decks provide air to a Variable Air Volume (VAV) mixing box at each temperature-controlled zone within the building. Each occupied

a. Exterior view.



b. First floor plan (not to scale).

Figure 1. CRREL laboratory addition.

Table 1. Wind and temperature during the air change measurements of the CRREL laboratory addition.

1991	Outdoor temperature (°C)	Wind speed (m/s)	Wind direction (degrees)*
24 Jan	–4.1	4.3	245
30	0.6	1.3	055
31	–6.3	2.2	007
3 Feb	9.7	2.1	210

*Degrees from true north.

floor of the laboratory addition is divided into zones served by VAV mixing boxes as follows: 1) basement—16 zones, totaling 6000 m^3, 2) first floor—21 zones, totaling 6800 m^3 (Fig. 1b), and 3) second floor—11 zones, totaling 2725 m^3. A single return air fan serves the building.

The laboratory addition temperature is controlled during winter as follows: Makeup air comes through a heat exchanger, which has glycol that is warmed by reclaimed heat. The heat exchanger turns on at outdoor temperatures below 18°C. Only in extreme cold is steam heat required, which enters a mixing chamber that is also fed by the return air fan. In weather colder than freezing, the main air exhaust is closed and return air recirculates through the cold and hot decks; air exhausts through leaks. In warmer weather some air is exhausted. Consequently, during the winter, the air change rate in the building should be a function of heat load.

Unlike many such buildings with central HVAC, the laboratory addition has operable double slider windows, which result in leaks around the sashes. The building has four personnel doors at the basement level and one each at the subbasement and second floor levels. There is a rolling overhead door at the basement and subbasement levels.

Test conditions

Four tests were conducted in January and February 1991 on 24, 30, 31 January and 3 February. In all four cases, the building was essentially unoccupied, because each test was done after business hours. The building is operated manually, with the same settings night and day. Table 1 shows the winds and temperatures during the measurements.

Test procedure

To achieve a target initial concentration of 1×10^{-9}, 15 cm^3 of SF_6 was released in the hot deck side of the HVAC system in the main mixing chamber where return and fresh air are combined. The tracer gas was released at 5 p.m. each of those days. In the first three tests, an automatic sampler was placed in the return air plenum for the entire building. All samplers were set to take twelve 30-cm^3 air samples, each lasting for 5 minutes, sequentially for an hour, starting when the gas was released.

Spatial samples were taken when, on 3 February, samplers were placed in two locations on the first floor and at one location on the second floor, as well as the return air plenum. All were programmed to sample simultaneously. In addition, manual samples of air in the building were obtained with syringes prior to the tracer gas release to test for existing tracer gas or other contaminants that might confound accurate measurement of the tracer gas.

Test results

Figure 2 shows that the tracer gas decay rate was about two times higher on 24 January (2.7 h^{-1}) than it was on 30, 31 January or 4 February (0.97, 0.88 and 1.26 per hour). These figures are well above the default ASHRAE 62-1989 standard minimum air change value of 0.4 h^{-1} for this type of building. The figure does not show a clear correlation of tracer gas decay rate with either wind speed or difference in temperature between indoors and outdoors. However, the tracer decay rate more closely reflects the trend of wind speed than of temperature difference.

Ideally, the concentration of tracer gas in the return air will offer a physically averaged concentration in all zones. Figure 3 shows that on 3 February

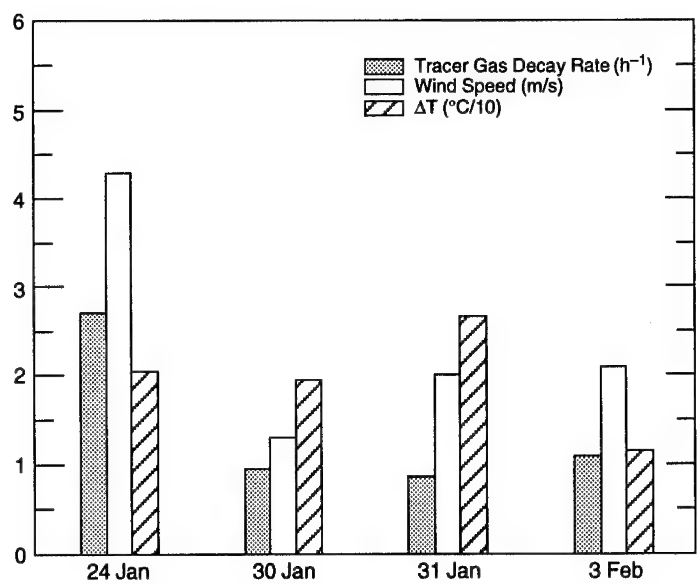


Figure 2. Measured tracer gas decay rate, wind speed and indoor–outdoor temperature difference in the CRREL laboratory addition.

the average concentration of the three spatial sampling locations within the laboratory addition closed to within 20% of the return air value within 15 minutes after the tracer gas was released. However, one space never came within 20% of the concentration measured at the return air plenum.

Test analysis

We would expect that air exchange rate, as modulated by the HVAC system, would be a function of outdoor temperature. There is no such correlation. Figure 2 suggests that a more plausible correlation would be between wind speed and tracer gas decay rate. However, there are too few data to support this.

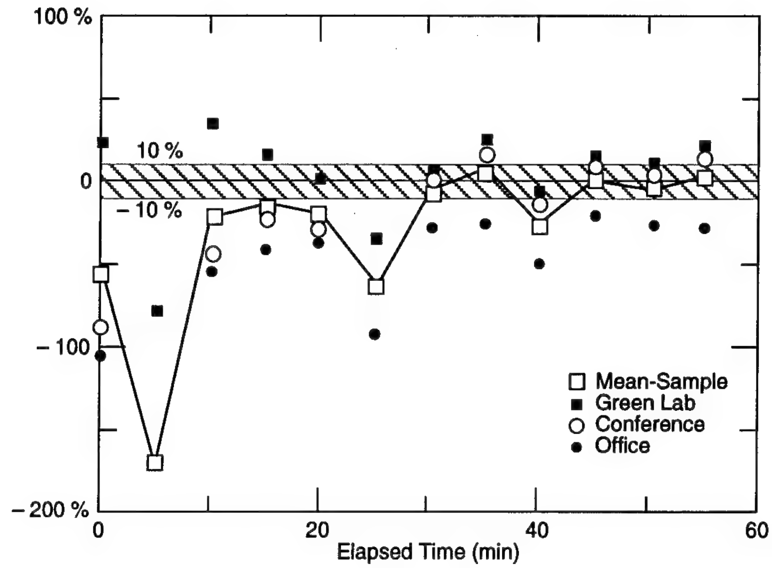


Figure 3. Tracer gas concentration as a percentage difference from return air concentration on 3 February 1991 in the CRREL laboratory addition.

The tracer gas concentration in the return air was within 20% of the average concentration of a few samples from spaces within the building after 15 minutes. After 45 minutes the sample average and the return concentrations were within 5% of each other. This tends to confirm that the tracer gas concentration in the return air is an unbiased physically averaged concentration for all zones. However, the difference between the tracer gas concentration in each space that was tested and the concentration in the return air plenum suggests less than ideal mixing. From the time series samplings of 3 of the 48 zones, we can expect with 95% confidence that the tracer gas concentration in each zone will be only within about 45% of the concentration in the return air after 30 minutes.

Another measure of whether it is realistic to idealize the building as a single zone is whether each region within the building exhibited similar tracer gas decay rates. A comparison of the tracer gas decay rate of each of the individual spaces sampled (Table 2) with the whole building (1.1 h^{-1}), as sampled at the return air plenum, shows that the individual spaces, which fit the constant tracer gas decay rate assumption, were quite different from the building as a whole.

The laboratory addition has suspended ceilings in the areas served by HVAC equipment on the first and second floors. This means that about one-third of the HVAC-served volume has poor mixing between the occupied and mechanical spaces. As a result, it would be difficult to determine the extent that tracer gas actually leaves the building without also determining the extent that it enters the mechanical spaces above the ceilings.

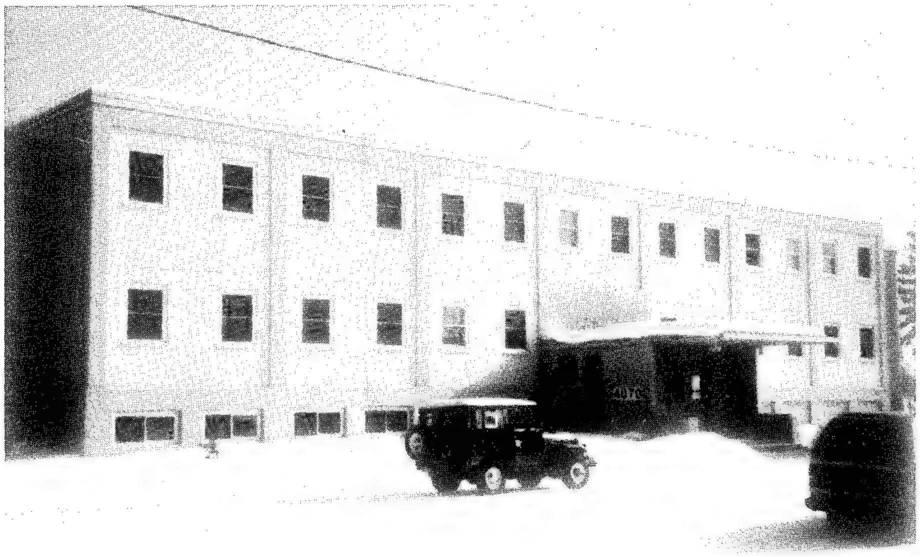
The tracer gas decay technique does not require an assumption of constant gas decay rates. However, we may determine to what extent the data deviate from a constant value with confidence limits. Confidence intervals taken at the 95% level about the mean tracer gas decay rates (Table 3) suggest that the air change rate is within about 45% of each mean value measured.

Table 2. Differences in tracer gas concentration between individual zones and the return air in the CRREL laboratory addition.

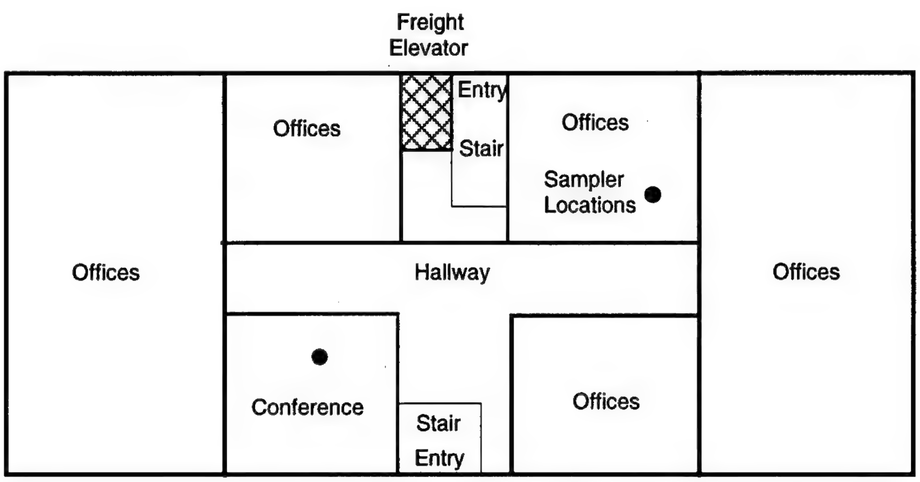
Location	*Floor*	*Tracer gas decay rate*	*% Difference from return air*
Laboratory	1	1.2	9
Office	1	1.7	55
Conference	2	2.1	91

Table 3. Tracer gas decay rates in the CRREL laboratory addition.

	Mean tracer gas decay rate (h^{-1})	*Confidence limit for air change rate (h^{-1})*
24 Jan 91	2.7	1.0
30	0.97	0.62
31	0.88	0.31
3 Feb 91	1.1	0.48



a. Exterior view.



b. First floor plan (not to scale).

Figure 4. Building P4070.

**Fort Wainwright—
administrative building P4070**

Building

P4070 is a 4000-m^3 administrative building of concrete slab construction with concrete masonry infill. It has a heating system that incorporates forced hot air and circulating hot water perimeter heat. The heat source is steam from a central plant. The building (Fig. 4a) has two stories plus a basement that accommodate office, laboratory, workshop and storage space for two tenants.

Zone

P4070 is served by a single fan unit with heat recovery via a connected pair of fin-tubed heat exchangers in the exhaust and the intake air streams. A fixed fraction of air is recirculated, as well. Air circulates throughout the building via ductwork that has fixed dampers to balance distribution. During much of the year, the building relies on operable windows for ventilation and temperature control. Because the control of heat in the building is poor, upstairs windows are sometimes open at extremely low temperatures. The basement level has an outdoor ramp

Table 4. Wind and temperature during the air change measurements of building P4070.

	Outdoor temperature (°C)	*Wind speed (m/s)*	*Wind direction (degrees)**
11 Dec 1991	−18	Calm	N/A
28 Mar 1992	−12	Calm	N/A

*Degrees from true north.

to an overhead door and a personnel door. There are two major personnel doors opposite one another in the middle of the building on the first floor (Fig. 4b). An open stairway and elevator shaft are also centrally located.

Test conditions

Two tests were conducted in P4070, one on 11 December 1991 and one on 28 March 1992. The building was occupied on 11 December and unoccupied on 28 March, a Sunday. Building P4070 is operated manually with the same settings night and day. The winds and temperatures were as shown in Table 4.

Test procedure

On 11 December 1991 about 4 cm^3 of SF_6 was released in the building intake air and 3 cm^3 was released as uniformly as possible on each floor to achieve a target initial concentration of about 3×10^{-9}. On 28 March 92, 15 cm^3 of SF_6 was released in the building, 5 cm^3 per floor, to achieve a target initial concentration of about 4×10^{-9}. The tracer gas was released at 3 p.m. in December and at 9 p.m. in March.

Three samplers each were placed on the first and second floors, with a sampler at each end of the floor and one in the middle near the stairwell. The basement received one sampler. Each sampler was set to take twelve 30-cm^3 air samples, each for 5 minutes, sequentially for an hour. Sampling began 30 minutes after the gas was released in December and at the same time that the gas was released in March. This distribution of samplers provided spatial sampling throughout the measurement period.

Test results

The tracer gas decay rate in December was 0.7 h^{-1} and in March was 1.4 h^{-1}. These figures are close to the default ASHRAE 62-1989 standard minimum air change value of 0.8 h^{-1} for this type of building. In December the average coefficient of variation of concentrations among sampled spaces was 21%; in March it was 51%.

Test analysis

In the two instances that the building was monitored for air exchange rate, the lower rate corresponded to the colder weather. The wind speed during both measurements was calm. Photographs of the building at the time of each measurement did not reveal differences in openings.

Analysis suggests that the building may be idealized as one zone, depending on how divergent the concentrations in the constituent parts of the building are. Confidence intervals at 95% on normalized departures of each concentration from its contemporaneous mean showed that the sample mean was within 6% of the true mean at any given time for the December data and within 9% for the March data.

The way that the tracer gas was distributed in the compartmented building appears to explain the differences in coefficients of variation in tracer gas concentration between December and March. In December, most of the tracer gas was introduced via the air-handling system. Thirty minutes after the tracer gas was released, the coefficient of variation of tracer gas concentrations among the places sampled was below 20% and it maintained an average of 21% after 45 minutes. In March, all of the tracer gas was introduced by apportioning gas from a syringe while researchers were walking around on each floor. Even after 45 minutes the coefficient of variation was around 50% and showing no signs of improvement. Excluding the break room data does not change the tracer gas decay rate but tightens the coefficient of variation to 27%.

Because the break room data have a different pattern and because the break room is much smaller than the other spaces monitored, the break room data have a disproportionate influence on the unweighted average of concentrations; therefore, it is reasonable to exclude them as outliers. The data for March show the progress of tracer gas concentration from the time of release at various sampling locations (Fig. 5). The tracer gas concentration in the break room over time decays directly from the first 5 minutes, whereas the concentrations in the other spaces reach a maximum after about 10 or 15 minutes and then decay.

Plots of C_{normal} (eq 1), the difference between the mean concentration at any given time and the concentration in each sampled space, show trends toward better mixing within the building. Figure 6a shows the December values trending to within 10 ± 5% of the normalized mean (scaled to equal one).

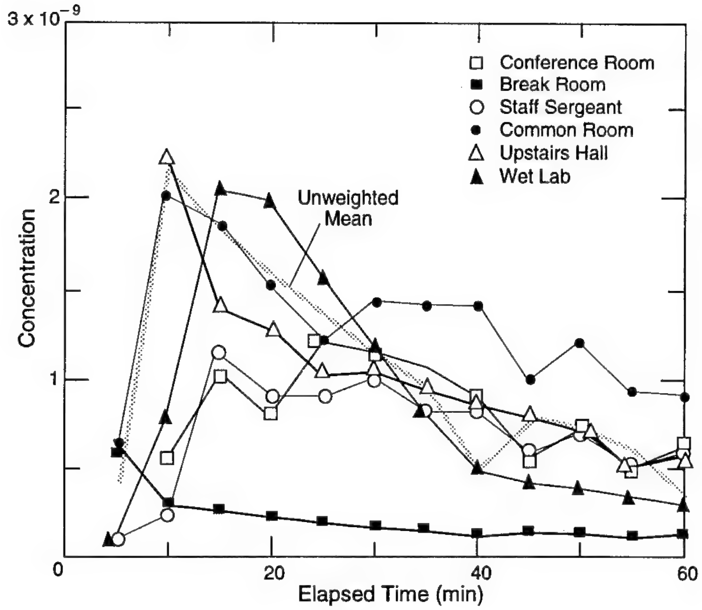
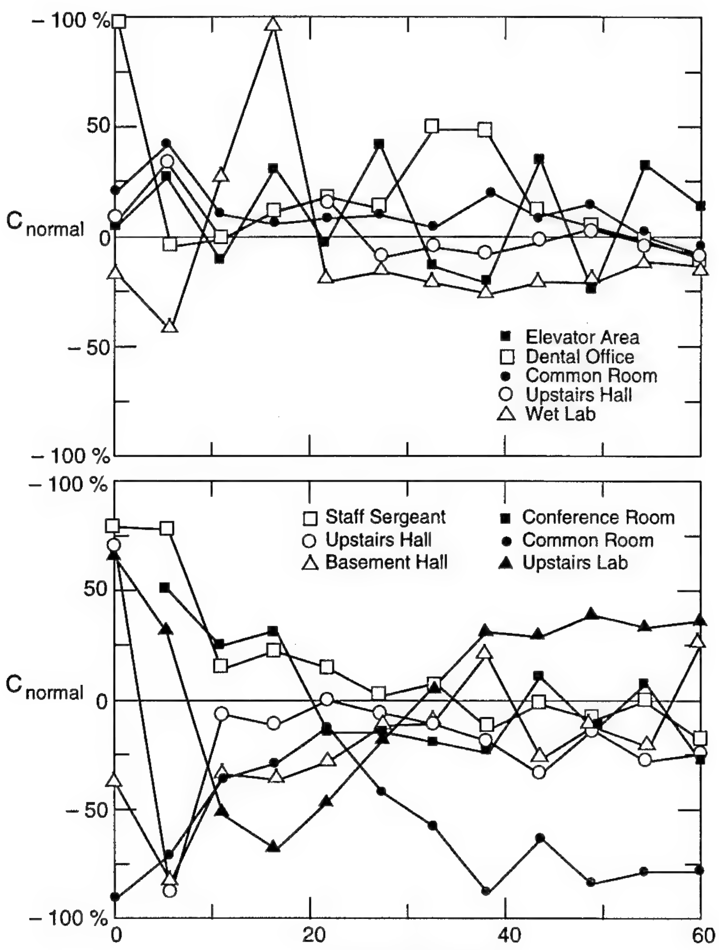


Figure 5. Tracer gas concentrations in March 1992 in building P4070.



a. December 1991.

b. March 1992.

Figure 6. Difference between average and within-space concentrations, building P4070.

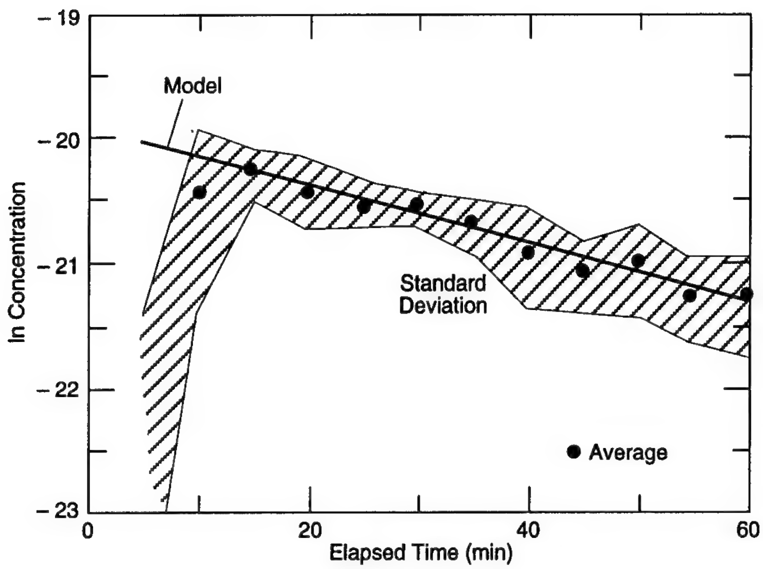


Figure 7. Standard deviation, average and regression of tracer gas concentrations, March 1992, building P4070.

Figure 6b shows that the March values dipped to within 8 ± 8% of the normalized mean but then rose again to 27 ± 20%. However, four of the spaces were much closer to the normalized mean: 17 ± 16%. The upstairs laboratory and a common room departed significantly from the mean.

As mentioned before, the tracer gas decay technique does not require an assumption of constant tracer gas decay rates. Figure 7 shows that even the mean March data fall on a straight line. However, we may determine to what extent the data deviate from a constant value with confidence limits. Calculations show that we may assume with 95% confidence that the tracer gas decay rate remained within about 12% of its mean value in December and within 10% in March.

Fort Richardson—building 666

Building

Building 666 is a barracks of concrete slab construction with masonry in-fill that has been recently renovated. It (Fig. 8a) has three stories above a partially buried basement, for a total volume of 10,000 m^3, mechanical ventilation with heat recovery, and wall-mounted steam convectors to supply heat from a central plant. In addition, the building has a 3000-m^3 wing served by a separate ventilation system.

Zone

This building can not be easily idealized as a single zone because of the many locked rooms that receive ventilation independently and the many operable windows. In addition, each bathroom has an exhaust fan. Enlisted personnel have communal latrines; officers and noncommissioned officers have private bathrooms. A central stair well connects the floors (Fig. 8b). Temperature is often controlled in such barracks, not with a thermostat, but by the troops opening windows when the building is too hot.

The mechanical ventilation incorporates air intake and air exhaust fans. A tilting heat-recovery coil spans the adjacent intake and exhaust air streams and extracts heat from the exhaust air and transfers it to the intake air, where there are also steam preheat and reheat coils.

Test conditions

Two tests were conducted in building 666 on 24 and 25 April 1991. The building was occupied on both days. It is operated manually with the same settings night and day. The winds and temperatures were as shown in Table 5.

Test procedure

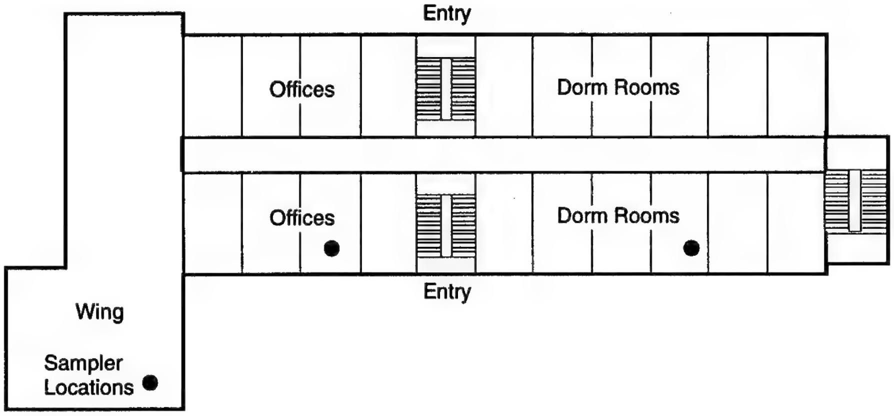
On 24 April, 13 cm^3 of SF_6 tracer gas was released in the building air intake plenum to achieve a target

Table 5. Wind and temperature during the air change measurements of building 666.

	Outdoor temperature (°C)	*Wind speed (m/s)*	*Wind direction (degrees)**
24 April 91	8.3	4.1–7.7	100
25 April 91	9.4	2.1	270

*Degrees from true north.

a. Exterior view.



b. First floor plan (not to scale).

Figure 8. Building 666.

initial concentration of 1×10^{-9}. On 25 April, 26 cm^3 of SF_6 tracer gas was released in the same way to achieve a target initial concentration of 2×10^{-9}.

Seven automated samplers were placed throughout the building each time. One sampler was placed in each of the following areas: basement, second floor, third floor and penthouse return air plenum. The first floor received two samplers. The first floor wing received a sampler to determine how well it coupled with the main building. Each sampler was set to take twelve 30-cm^3 air samples, each 5 minutes long, sequentially for an hour, starting when the gas was released at 6 p.m. each day. This approach provided both time series and spatial sampling in the building.

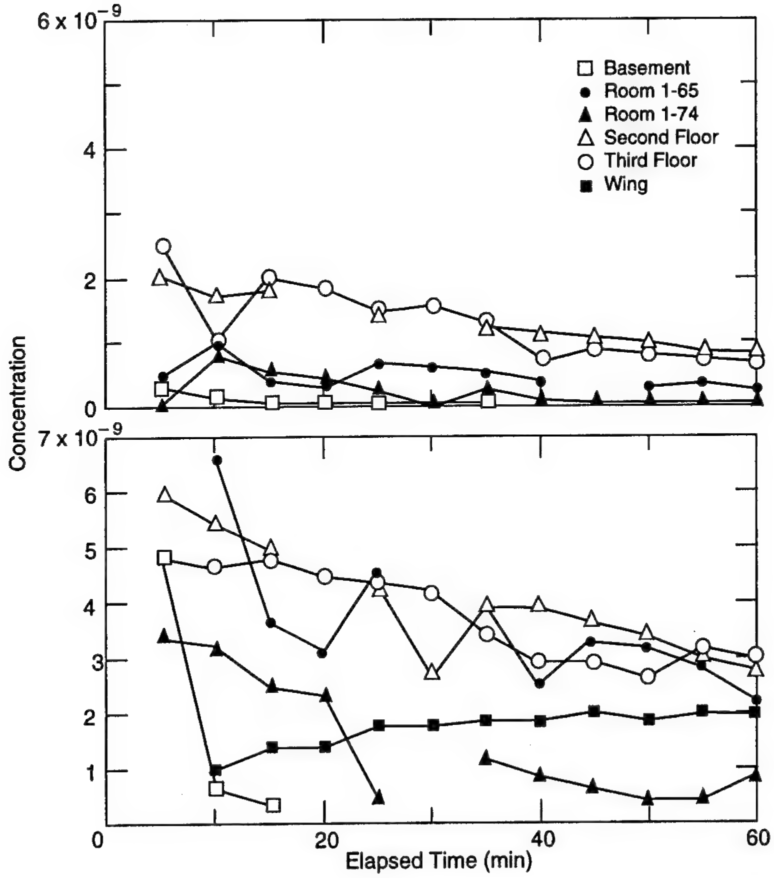
Test results

Table 6 shows the tracer gas decay rates measured in building 666. These figures are, on the average, above the default ASHRAE 62-1989 standard minimum air change rate value of 0.5 h^{-1} for a dormitory like this building. The following *Test Analysis* section discusses the two means employed for characterizing air change rate: the mathematical average of the separate spaces sampled and a physical average for the building, as measured at the return air plenum.

Uniform distribution of tracer gas within the building should cause the tracer gas concentrations

Table 6. Air change rates in building 666.

	Tracer gas decay rate (h^{-1})		
	Average of all data	*Select data*	*Measured at return air*
24 April 91	0.67	0.74–0.17	1.9
25 April 91	0.88	1.12–0.21	2.2



a. 24 April 1991.

b. 25 April 1991.

Figure 9. Tracer gas concentrations, building 666.

in the sampled spaces to trend towards the same value. Figure 9 shows nonuniform tracer gas concentration values. These values are much more uniform on 24 April, with a coefficient of variation of tracer gas concentration at any given time of around 10% for select data, than on 25 April, with a coefficient of variation of about 70%.

The 95% confidence limits about the air leakage rate of select data were 23 and 19% of the calculated values. This indicates how far from a constant value the air leakage rate may have been during the hour of measurement.

Test analysis

There are too few days of record when air change measurements were made to correlate tracer gas decay rate with wind speed or temperature.

Some time series data were excluded from the analysis. On both days, the first-floor wing was clearly not part of the zone. The data in Figure 9 show the tracer gas concentration constant at a low level (Fig. 9a) or slowly rising throughout the period (Fig. 9b). The basement's tracer gas decay behavior is also radically different from that of the rest of the building. It is designed to have more than twice the air change rate of the other floors; also, every time the outside door opens, there is a significant exchange of the basement's warm air with cold outdoor air. On both days the tracer gas concentration in room 74 was much less than elsewhere. The data from this room were excluded on 24 April and included on 25 April.

The return air tracer gas concentration and the average concentration of the spaces sampled suggest that either of the two averages may be significantly biased. Figure 10 shows C_{bias}, the normalized difference between the tracer gas concentration at the return air plenum and the concentrations at the sampled locations (eq 2). On both days the concentration in the plenum decayed more rapidly than in the sampled spaces.

The design air change rate for the whole building is 1.55 h^{-1}. If the tracer gas injected into the air intake were uniformly distributed in the building and if it were possible to sample where the air return joins the vertical riser at each floor, and with minimal

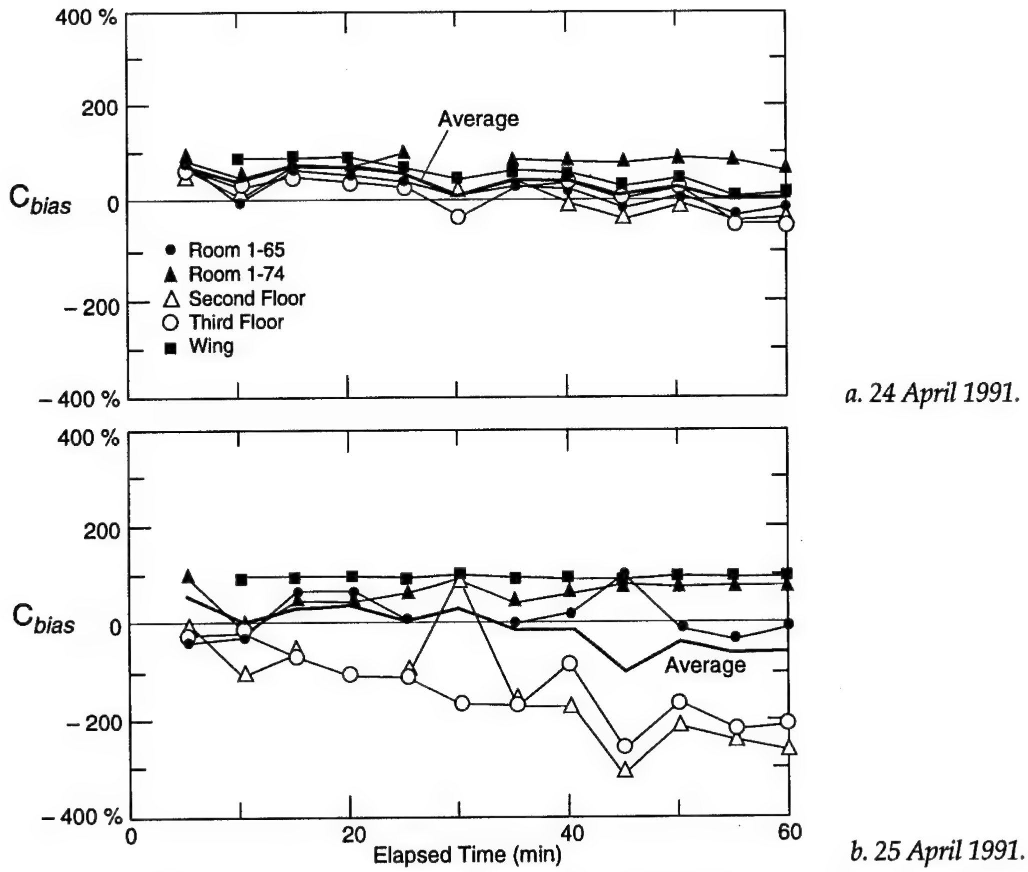


Figure 10. Difference between air-return and within-space concentrations, C_{bias}, building 666.

Table 7. Design air change rate and measured tracer gas decay rates in building 666.

	Tracer gas decay rate (h^{-1})		
		Measured	
Floor	*Design*	*24 April*	*25 April*
3	1.25	0.72	1.4
2	1.25	0.73	1.0
1	1.12	1.5	2.4
Basement	2.56	6	6.6
Averages	1.55	4.7	2.8

communication between floors, then the tracer gas decay rates measured for each floor would represent air exchange rates, as shown in Table 7.

The design air change rate in the basement is more than double the air change rate for other parts of the building. This suggests that the air sampled in the return air plenum represents a disproportionately high fraction of basement air, which thereby biases the sample. The sampler data in the basement and on the first floor suggest that the ventilation rates are much too high; those in the first floor wing suggest that the ventilation rates are much too low.

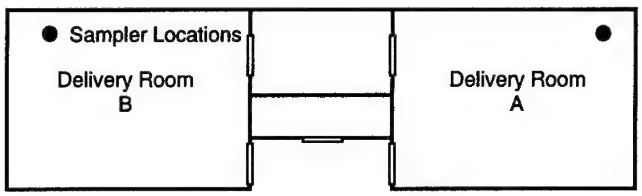
The lack of adequate mixing evident in Figure 9 and the significant C_{bias} evident in Figure 10 suggest that this building is unsuited for the tracer gas decay technique, unless the building is substantially reconfigured with open doors and active mixing of tracer gas with fans. Such an approach is not easy to do in an occupied barracks. Even when barracks are unoccupied, each door has a separate key with no master, which makes access difficult.

**Fort Wainwright—
Bassett Army Hospital**

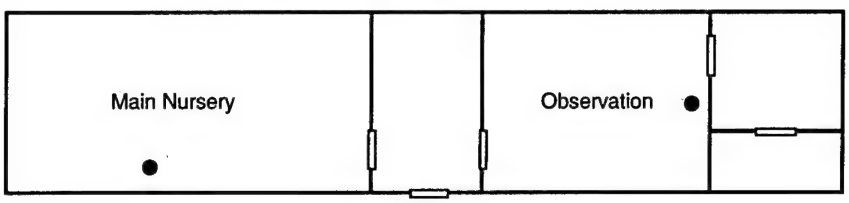
Building

Bassett Army Hospital (Fig. 11a) has perimeter steam heat and two ventilation systems, one for the operating, delivery and nursery suites, and one for the rest of the facility. A central plant provides the steam heat.

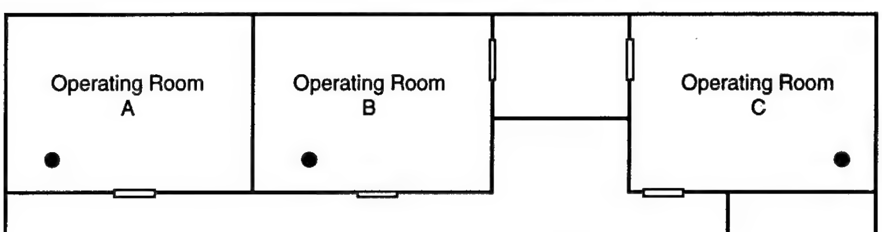
a. Exterior view.



b. Delivery rooms (not to scale).



c. Nursery (not to scale).



d. Operating rooms (not to scale).

Figure 11. Bassett Army Hospital.

Zone

The criterion air change rate for the operating suite is 12 h^{-1}. To meet this, the HVAC system employs 100% outside air—there is supposed to be no recirculation of indoor air. This study was confined to the fifth-floor delivery room suite (128 m^3, Fig. 11b) and nursery suite (244 m^3, Fig. 11c), and the sixth-floor operating room suite (271 m^3, Fig. 11d), which are served by a single heating and ventilating system. Unlike most of the hospital, there are no windows to the outdoors. The exterior walls are opaque and have no apparent leaks.

Table 8. Wind and temperature during the air change measurements in Bassett Army Hospital.

	Outdoor temperature (°C)	*Wind speed (m/s)*	*Wind direction (degrees)**
30 Mar 92	–1.7	0.5	210

*Degrees from true north.

Test conditions

A single test was done in 1992 on 30 March 1990. The nursery space was occupied, but the operating and delivery rooms were not. All doors were closed, except the doors within the nursery. Table 8 shows the winds and temperatures during the measurement.

Test procedure

Because of the high air change rate anticipated, a high target concentration of 5×10^{-9} was chosen. Therefore, 4 cm^3 of SF_6 was released into the intake side of the air handling unit. Seven automated samplers were placed throughout the operating, delivery and nursery suites. One sampler was placed in each of the following areas: operating rooms A, B and C, delivery rooms A and B, the main nursery and the observation room adjacent to the nursery. The sampling began when the gas was released at 8:30 a.m. This approach provided both time series and spatial sampling in the zone.

Test results

Table 9 shows the calculated tracer gas decay rates. The sixth-floor operating room suite and the fifth-floor delivery and nursery suite are each compartmented areas. Any air mixing between areas would occur by opening of doors, since each is designed to be isolated from the others. After 15 minutes the coefficient of variation of tracer gas concentration (Fig. 12a) within the operating room suite came down to 9%, but quickly thereafter diverged to more than 35%. The concentrations in delivery rooms A and B became further apart. Furthermore, the reappearance of a spike in tracer gas concentration in delivery room B suggests recirculation of air carrying tracer gas (Fig. 12b). The tracer gas concentrations in the nursery suite (Fig. 12c) were not close to one another.

The tracer gas decay rates (Table 9) varied between a low of 3.2 h^{-1} in the nursery and a high value of 9.6 h^{-1} in operating room B. The values in the operating suite were between 6.6 and 9.6 h^{-1} with an average value of 8.5 h^{-1}. In each case

Table 9. Tracer gas decay rate measurements in Bassett Army Hospital.

Sampling location	*ASHRAE criterion air change rate (h^{-1})*	*Measured tracer gas decay rate (h^{-1})*
Operating room A	4	6.5
Operating room B	4	9.6
Operating room C	4	9.3
Delivery room A	4	3.8
Delivery room B	4	7.3
Main nursery	2	3.2
Observation	2	5.2

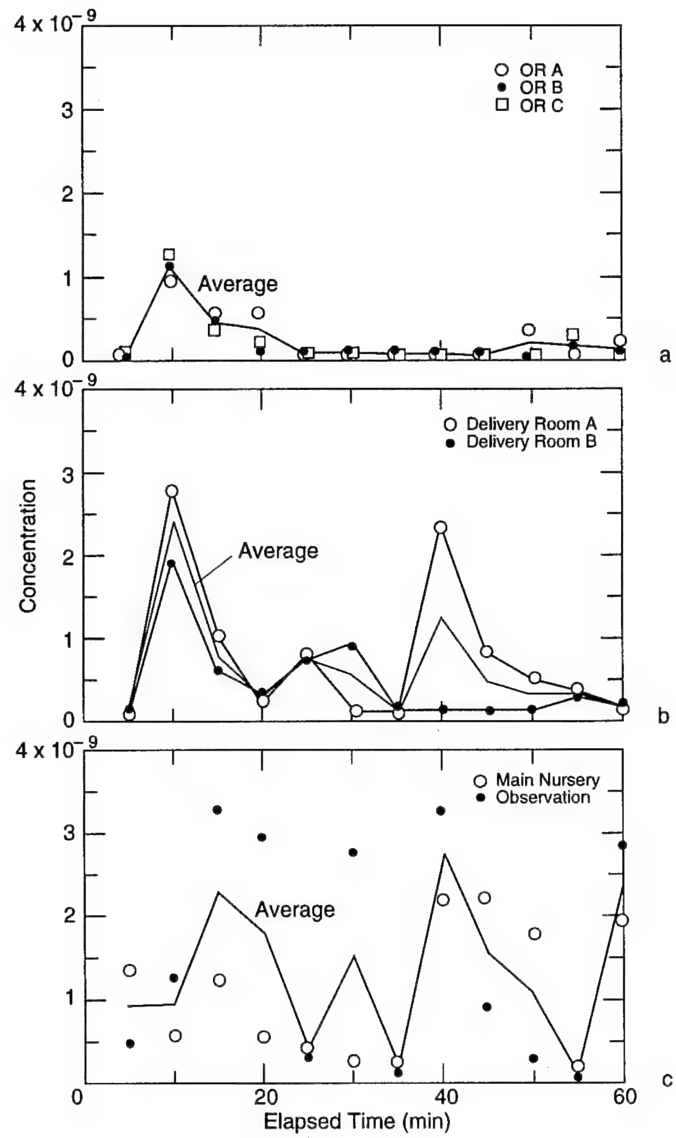
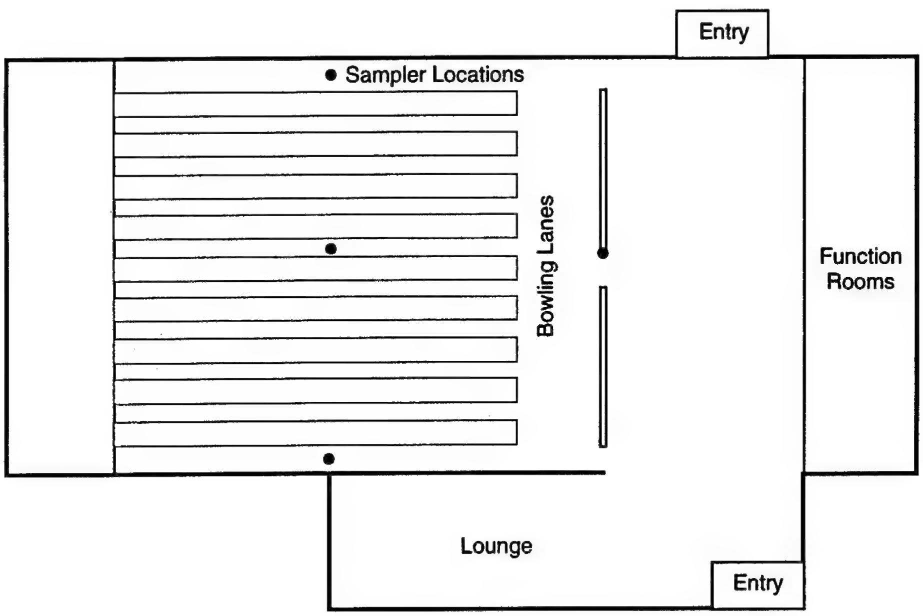


Figure 12. Tracer gas concentrations in study areas of Bassett Army Hospital (a—operating rooms A, B, and C; b—delivery rooms A and B; c—nursery).

a. Exterior view.



b. Plan (not to scale).

Figure 13. Bowling alley P3702.

the tracer gas decay rates were variable. These figures are above the default ASHRAE 62-1989 standard minimum value of 3.9 h^{-1} for an operating or delivery room and the value of 2.1 h^{-1} for a recovery room, in the case of the nursery.

Test analysis

A properly functioning ventilation system that runs at a constant rate to meet air change standards should cause a uniform decay rate of tracer gas concentration. There was no such uniform rate. Instead, the concentration fell dramatically in the first half hour, but in the second half hour it rebounded in many of the spaces measured. The rates of flow through each operating and delivery room tested was sufficiently high to greatly overshadow any leakage between rooms. If there was any cross-mixing of tracer gas from one operating or delivery room to another, it would have to have been via the ventilation system. The main nursery and observation room were connected by an open doorway during the measurement.

We may reasonably postulate that each operating room, delivery room and nursery was a separate zone, individually influenced primarily by the ventilation system. Cross mixing was probably negligible. We could study this effect by releasing tracer gas in each space in turn and sampling for it in adjacent spaces.

Fort Wainwright—bowling alley P3702

Building

Building P3702, a 14.3×10^3-m^3 bowling alley (Fig. 13a), was approximately doubled in size in 1992. The major portion of this one-story building is an open space for alleys. There are some ancillary spaces for function rooms, video games and a lounge.

Zone

Two heating and ventilation systems serve P3702, one for the new section of the building and one for the old. The building has few windows, and the public enters at either end through double sets of doors that form an arctic entry. For this experiment, P3702 was idealized as a single zone (Fig. 13b).

Test conditions

The test was done on 27 March 1992. Table 10 gives the wind and temperature data. Both heating and ventilation systems were apparently in operation, although verification was difficult.

Test procedure

On 27 March at 4 p.m., 5 cm^3 of SF_6 tracer gas was released in the building air intake of the new portion and another 5 cm^3 was released in the main space of the old portion of the building to get a target initial concentration of 1.5×10^{-9}.

Four automated samplers were placed throughout the main portion of the building. Samplers were placed in the center of lanes at the right, middle and left of the bowling alley (encompassing the new and original portions) and one sampler was placed in the middle of the aisle that provides public access to all the lanes. Sampling began when the gas was released. This approach provided both time series and spatial sampling in the building.

Table 10. Wind and temperature during the air change measurements in building P3702.

	Outdoor temperature (°C)	*Wind speed (m/s)*	*Wind direction (degrees)**
27 Mar 92	–5	0.5	240

*Degrees from true north.

Test results

Over the course of an hour, the uniformity of the tracer gas concentration improved from a coefficient of variation among sampling places at the same time of 110% initially to 50% after 15 minutes (Fig. 14). After that, the coefficient of variation never dropped below 50%, and it wandered as high as 80%. The average tracer gas decay rate was 0.5 h^{-1}. Since there never really was uniform mixing during the hour of sampling, it is impossible to characterize the air change rate as constant or not. ASHRAE 62-1989 requires a minimum air change flow of 2.5 L/s m^2 in

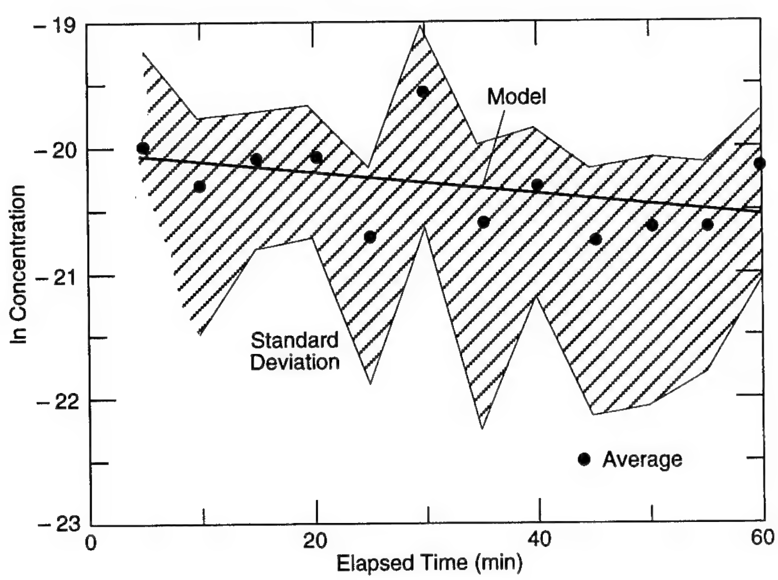
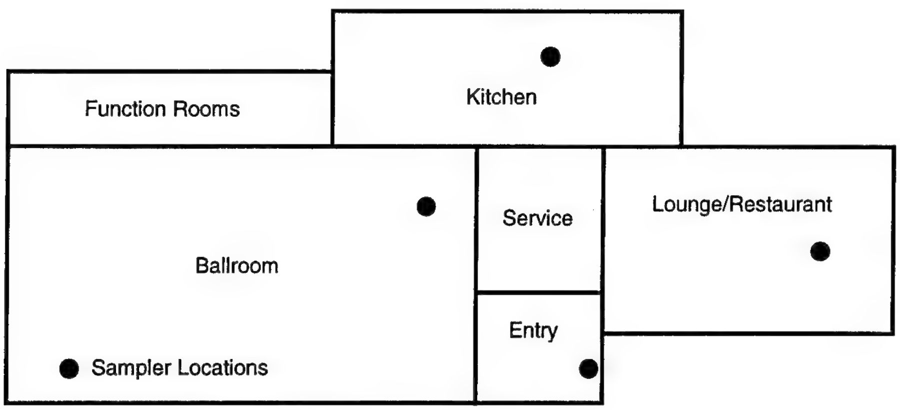


Figure 14. Logarithm of mean, standard deviation and regression model of tracer gas concentrations in the bowling alley.

a. Exterior view.



b. Plan (not to scale).

Figure 15. Junior Enlisted Club.

sporting arenas (which for this building's volume implies 9 h^{-1}), although it does not list bowling alleys specifically. The measured tracer gas decay rate is well below the default value from ASHRAE 62-1989.

Test analysis

In this test the environmental and occupancy conditions remained essentially constant. The confidence interval about the value of the slope of the regression line and hence the average tracer gas decay rate over the period of measurement was ±0.1% of the average value. This was despite the dominant error in determining air change rate being the lack of satisfactory uniformity of tracer gas concentration at any time during the measurement. The confidence interval about the last half hour of concentration data was 110% of the mean. ASTM E741 suggests that we may expect adequate mixing in a large single zone after approximately 30 minutes. This did not happen in P3702.

Fort Wainwright—Junior Enlisted Club

Building

The Junior Enlisted Club (Fig. 15a) was under construction at the time of testing. It is a 5.2×10^3-m^3 multipurpose building that includes restaurant dining, a lounge and a ballroom, plus smaller function rooms.

Zone

The building has fan units serving the ballroom, the lounge–restaurant and the kitchen (Fig. 15b). During the test the ventilation fans, which had not yet been balanced, were turned on.

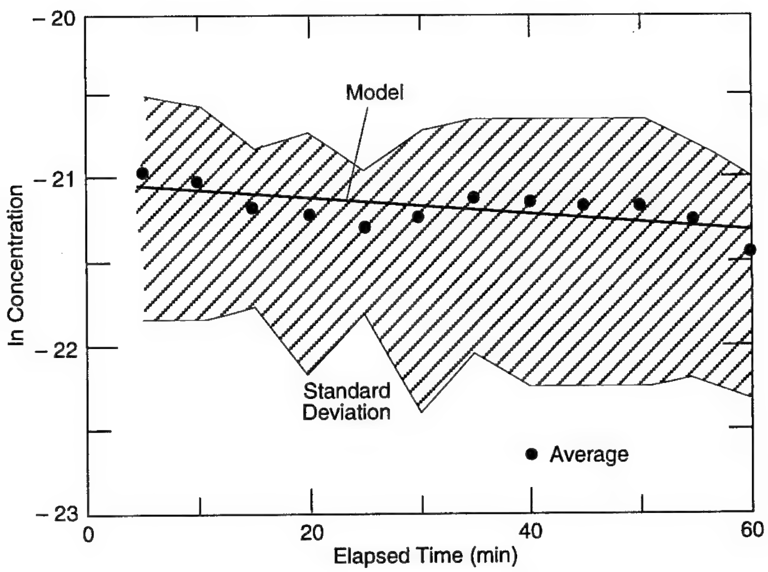


Figure 16. Logarithm of mean, standard deviation and regression model of tracer gas concentrations in the Junior Enlisted Club.

Table 11. Wind and temperature during the air change measurements in the Junior Enlisted Club.

	Outdoor temperature (°C)	*Wind speed (m/s)*	*Wind direction (degrees)**
30 Mar 92	–6.1	3.6	340

*Degrees from true north.

Test conditions

On 30 March 1992 the weather conditions were as shown in Table 11. The contractor was asked to run the still-unbalanced ventilation system, but it was not possible to confirm this because the fan room was locked. All windows and doors were closed. The construction crew had left the building when the gas was released.

Test procedure

On 30 March 1992 at 4:30 p.m., 25 cm^3 of SF_6 tracer gas was released in the lounge–restaurant, the kitchen, the ballroom and the entryway in proportion to the volume of each space to achieve a uniform target initial concentration of 5×10^{-9}.

Five automated samplers were placed throughout the building. One sampler each was placed in the entryway, the lounge–restaurant and the kitchen, and two samplers were placed in the ballroom. Each sampler was set to take twelve 30-cm^3 air samples, each 5 minutes long, sequentially for an hour, starting when the gas was released. This approach provided both time series and spatial sampling in the building.

Test results

Over the course of an hour, the uniformity of the tracer gas concentration maintained a coefficient of variation of about 60%. The average tracer gas decay rate was 0.5 h^{-1}. Since uniform mixing never really took place during the hour of sampling, it is impossible to characterize the air change rate as constant or not. The measured tracer gas decay rate is well below the default ASHRAE 62-1989 standard minimum value of 3 h^{-1} for this type of building.

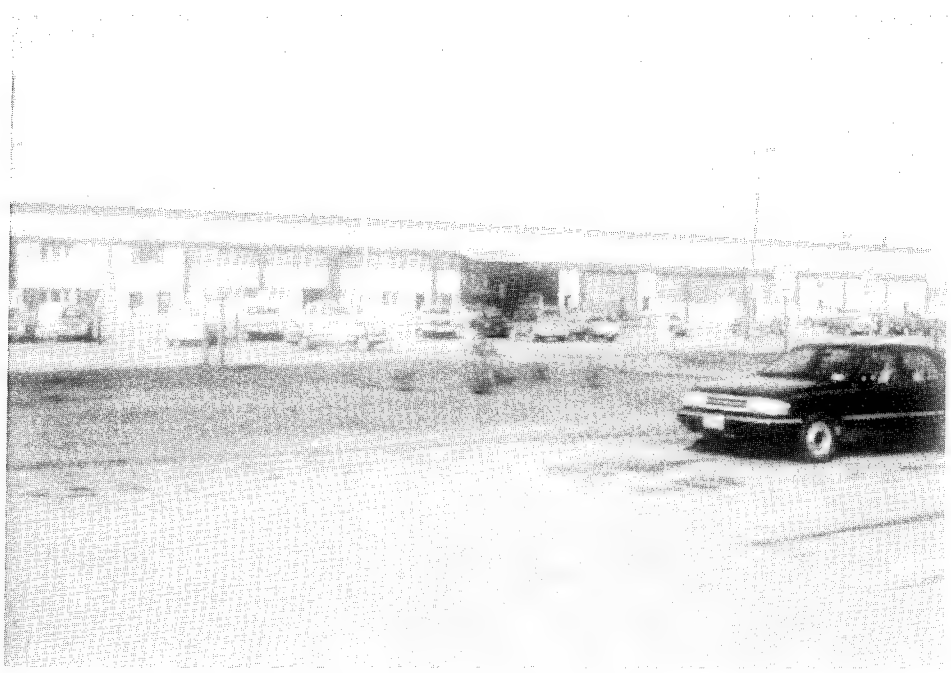
Test analysis

The uniformity of tracer gas concentration in this test was very low. Furthermore, the tracer gas decay rate was so low that it seems unlikely that the mechanical ventilation was in operation. The confidence interval for the slope of the regression in Figure 16 is ±0.03% of the slope or average tracer gas decay rate, while the confidence interval about the average concentration is 86%. The scatter of data suggests slight variations in tracer gas decay rate attributable to wind and temperature.

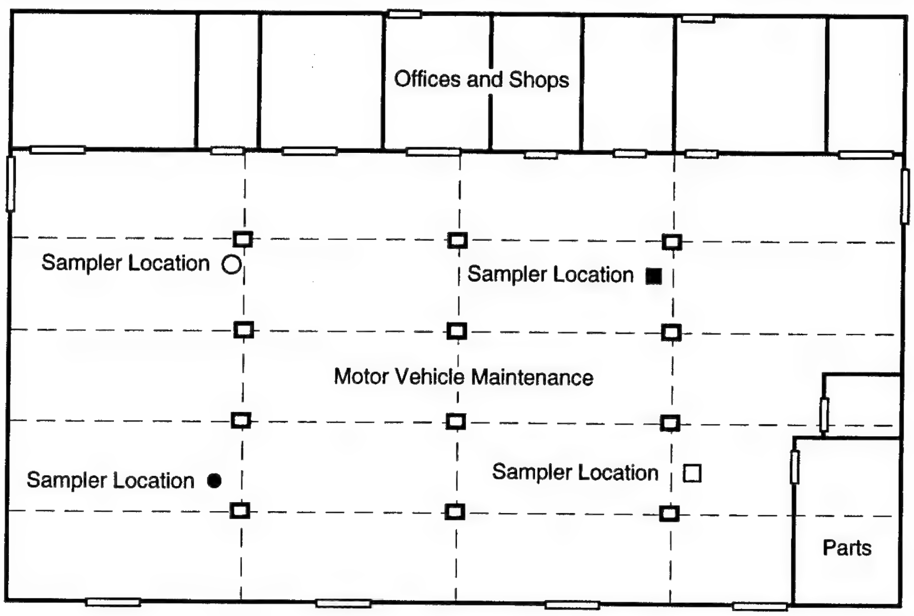
Fort Wainwright—DEH shop P3105

Building

The Directorate of Engineering and Housing (DEH) shop (Fig. 17a) comprises a 25×10^3-m^3 space, containing motor vehicle maintenance bays that were the subject of this study, and a two-story office and shop complex. The office and shop complex are walled off from the shop bays and have a separate ventilation system to minimize the incursion of vehicle exhaust fumes.



a. Exterior view.



b. Plan (not to scale).

Figure 17. DEH shop, building 3015.

Table 12. Wind and temperature during the air change measurements in DEH shop, building P3105.

	Outdoor temperature (°C)	*Wind speed (m/s)*	*Wind direction (degrees)*
10 Dec 92	–29	Calm	N/A

Zone

The motor vehicle maintenance shop (Fig. 17b) has ceiling-hung fan units that variously supply air, exhaust air and provide an automotive exhaust hook-up system.

Test conditions

On 10 December 1991 the weather was as shown in Table 12.

Test procedure

On 10 December 1992 at 4:50 p.m., 75 cm^3 of SF_6 tracer gas was released in the maintenance area in proportion to the volume of each space to achieve a uniform target initial concentration of 3×10^{-9}.

Four automated samplers were placed throughout the building. One sampler each was placed in the four quadrants of the shop bay area. They were

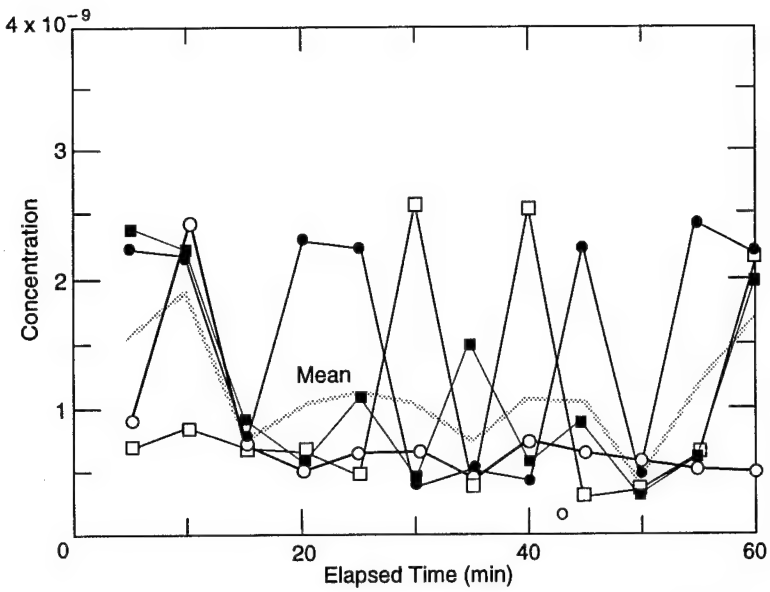


Figure 18. Tracer gas concentrations with their mean in the DEH shop, building 3015.

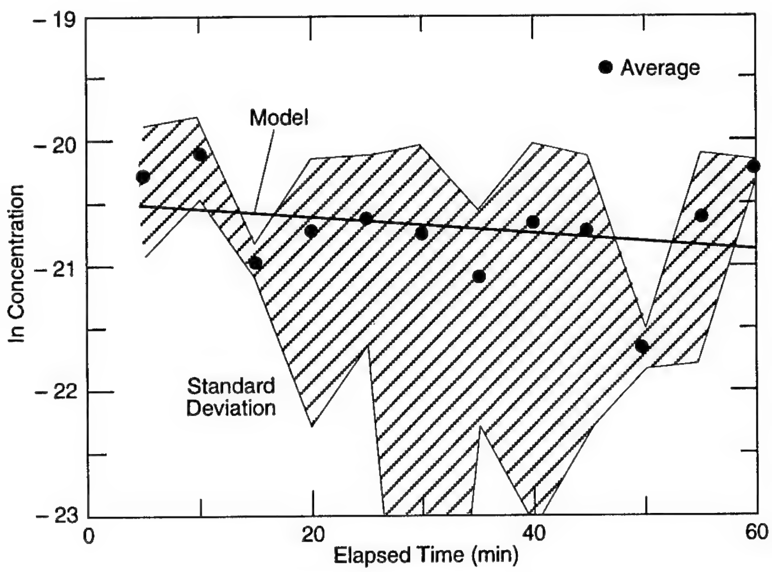


Figure 19. Logarithm of mean, standard deviation and regression model of tracer gas concentrations in the DEH shop, building 3015.

set to take twelve 30-cm^3 air samples, each 5 minutes long, sequentially for an hour, starting 40 minutes after the gas was released. This approach provided both time series and spatial sampling in the building.

Test results

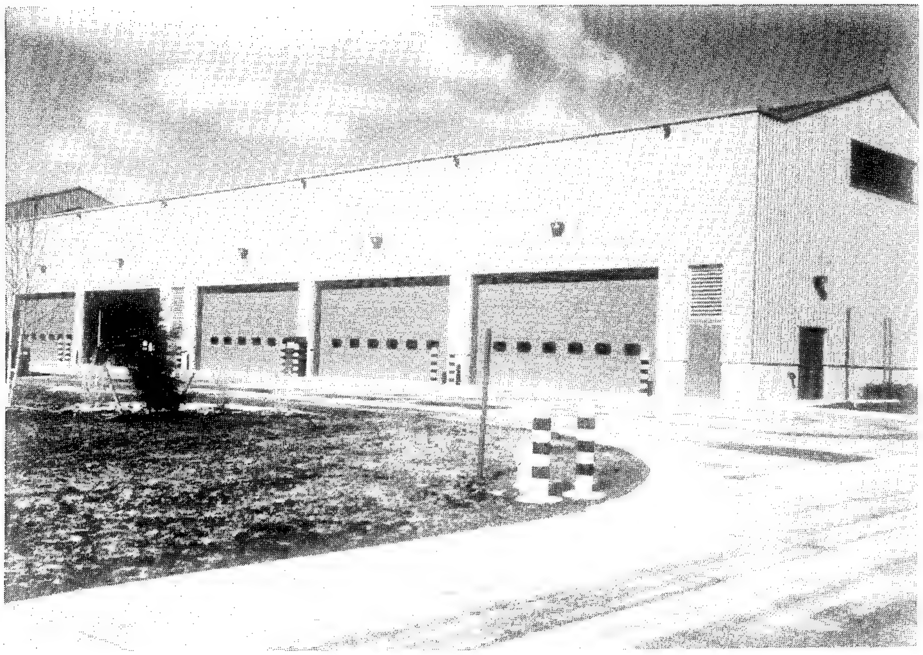
Over the course of an hour, the uniformity of the tracer gas concentration maintained a coefficient of variation of about 60%. If we can accept such nonuniform mixing, then the calculated average tracer gas decay rate was 0.4 h^{-1} over the hour of sampling. Since there never really was uniform mixing during the hour of sampling, it is impossible to characterize the air change rate as constant or not. The measured air change rate is well below the default ASHRAE 62-1989 standard minimum value of 5.4 h^{-1} for this sort of building.

Test analysis

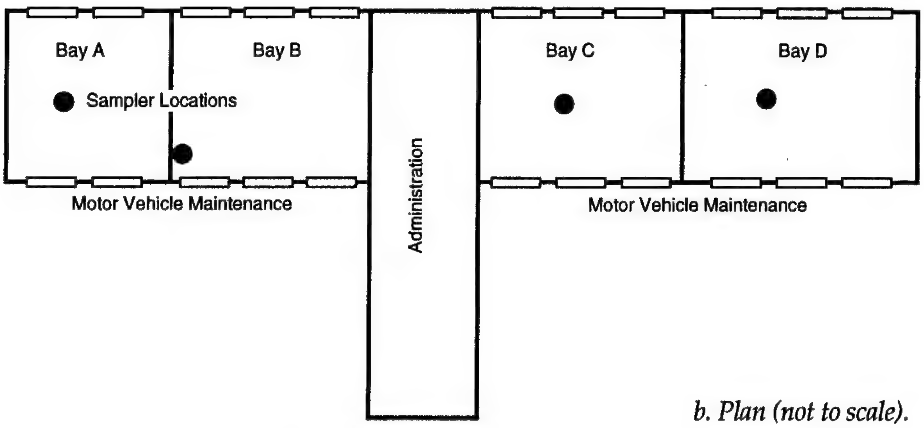
Initial air samples, obtained before the tracer gas release, suggested that an aerosol, probably a solvent used in the motor shop, was present that confounded the peak on the gas analyzer that represented the SF_6. If such a confounding source presents a constant background level, then the tracer gas decay would be identifiable as a superimposed signal.

The progress of the tracer gas concentrations at three of the four sampler locations suggested the intermittent operations of fans (Fig. 18). In the presence of a constantly emitted aerosol pollutant, fans would draw down the concentration and then permit its resurgence. This effect could occur either with intermittent ventilation or with intermittent mixing of the pollutant when unit heaters came on in the presence of constant background ventilation. These factors suggest a very unreliable measurement.

When the data are averaged and one standard deviation is calculated and plotted logarithmically (Fig. 19), they suggest an average calculated tracer gas decay rate of 0.4 h^{-1}. The confidence interval about the slope of the regression, and therefore the average tracer gas decay rate, was ±0.1% of the mean value. However, the confidence interval about the concentrations during the last half hour was only ±77%. The presence of rising average concentrations represents either a rise of aerosol concentration or reentrainment of the tracer gas.



a. Exterior view.



b. Plan (not to scale).

Figure 20. Vehicle maintenance shop, building P10670.

Fort Drum—unit motor vehicle maintenance building P10670

Building

The motor vehicle maintenance building, P10670 (Fig. 20), comprises a two-story office, flanked on either side by wings containing the shops. The two wings, containing motor vehicle maintenance bays, were the subject of this study. The east wing contains two 5.9×10^3-m^3 shops with three drive-through bays each. The west wing contains one 5.9×10^3-m^3 shop with three drive-through bays, and one 4.0×10^3-m^3 shop with two drive-through bays. The office complex and each of the shops are walled off from one another and connect via personnel doors.

Zone

The building has separate fan units serving each of the four shops and the center administrative section. The shop fans were rated about 4.7 m^3/s (10×10^3 ft^3/min) each. This corresponds to a design air change rate of about 2.9 h^{-1}.

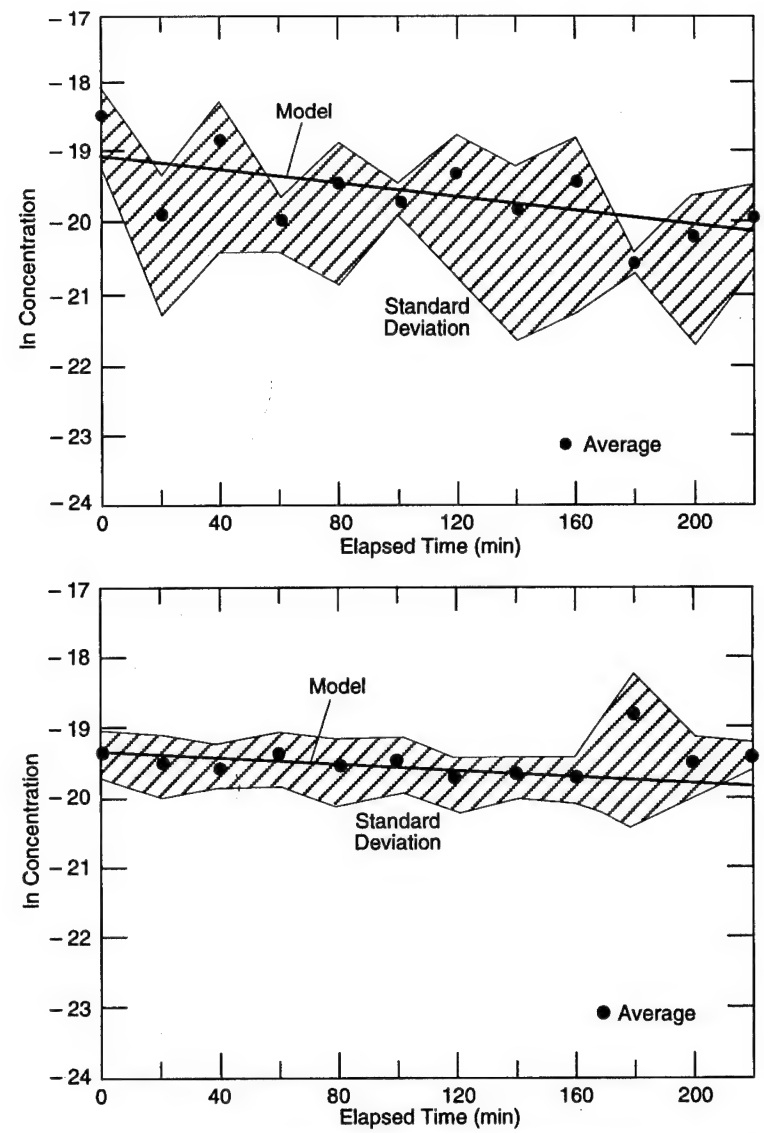
Test conditions

On 25 March 1991 the building was operated with the ventilation fans turned on, and on 26 March 1991 the building was operated with the ventilation fans turned off. Table 13 summarizes the temperature and wind conditions.

Test procedure

On both days at 4:35 p.m., 20 cm^3 of SF_6 tracer gas was released in proportion to the volume of each shop to achieve a uniform target initial concentration of about 1×10^{-9}.

On 25 March one of three automated samplers was placed in three of the four shop rooms in the building. On 26 March one of four automated sam-



a. 25 March 1991.

b. 26 March 1991.

Figure 21. Logarithm of the mean of the data and the regression model of tracer gas concentrations in the motor vehicle maintenance shop building P10670.

plers was placed in each of the four shop rooms in the building. Each sampler was set to take twelve 30-cm^3 air samples, each 20 minutes long, sequentially for an hour, starting when the gas was released. This approach provided both time series and spatial sampling in the building.

Table 13. Wind and temperature during the air change measurements in the motor vehicle maintenance building P10670.

	Outdoor temperature (°C)	*Wind speed (m/s)*	*Wind direction (degrees)**
25 Mar 91	3	2.5	260
26 Mar 91	9	2.4	150

*Degrees from true north.

Test results

On 25 March the average tracer gas decay rate for the four shops was 0.3 h^{-1}, with the uniformity of the tracer gas concentration among the four shops maintaining a coefficient of variation from 11 to 85% while the fans were turned on (Fig. 21a). On 26 March the average tracer gas decay rate for the four shops was 0.1 h^{-1}, with the uniformity of the tracer gas concentration among the three shops maintaining a coefficient of variation from 18 to 44% while the fans were turned off (Fig. 21b). Within each shop there was no test for uniform mixing. Table 14 re-

Table 14. Tracer gas decay rates at the sampling locations in the motor vehicle maintenance building P10670.

Maintenance shop	*Ventilation on*	*Ventilation off*
A	–0.7	0.2
B	—	0.3
C	0.2	0.1
D	0.8	0.1

Table 15. Confidence intervals for the average tracer gas decay rate and tracer gas concentration for each of two days in the motor vehicle maintenance building P10670.

	Percent of tracer gas decay rate	*Percent of mean concentration*
25 Mar 91	3	114
26 Mar 91	1	64

ports the tracer gas decay rate as if each shop were an autonomous zone. On both days, the measured tracer gas decay rates were well below the default ASHRAE 62-1989 standard minimum value of 5.4 h^{-1} for this type of building.

Test analysis

The tracer gas decay rate in Shop A being negative indicates that the shops cannot be regarded as unconnected with the ventilation system on. The rising tracer gas concentration must have come from an adjacent space. The individual regressions on the concentration data obtained in the four shops with the fans off supported the assumption that the tracer gas decay rates in each shop were constant over the period of sampling. Table 15 reports the confidence intervals for P10670 as a whole for average tracer gas decay rate in the shops and for average tracer gas concentration in the shops. Although there are diverse concentrations in the respective shops, it is possible to obtain an aggregate behavior from the average concentration.

Fort Drum—aviation maintenance and overhaul shop P2050

Building

The aviation maintenance and overhaul shop, P2050 (Fig. 22a), comprises a high hangar bay and an L-shaped support area with specialty shops and an administrative area. The 20.1×10^3-m^3 hangar accommodates the servicing of five or six helicopters at a time. The 9.7×10^3-m^3 support area contains a paint shop, prop and rotor shop, an avionics and electrical shop, hydraulics shops, a sheet metal shop, an engine repair shop, tool and supply areas and an administrative area with ready rooms. The functions within the support area are walled off from one another and the hangar and connect via personnel doors.

Zone

The building has separate fan units serving the hangar and the support areas (Fig. 22b). Their ratings were not recorded.

Test conditions

This test took place on the same days as the tests in P10670 (above). Table 13 summarizes the temperature and wind conditions. On 25 March 1991 the building was operated with the ventilation fans turned off. On 26 March 1991 the building was operated with the ventilation fans turned on.

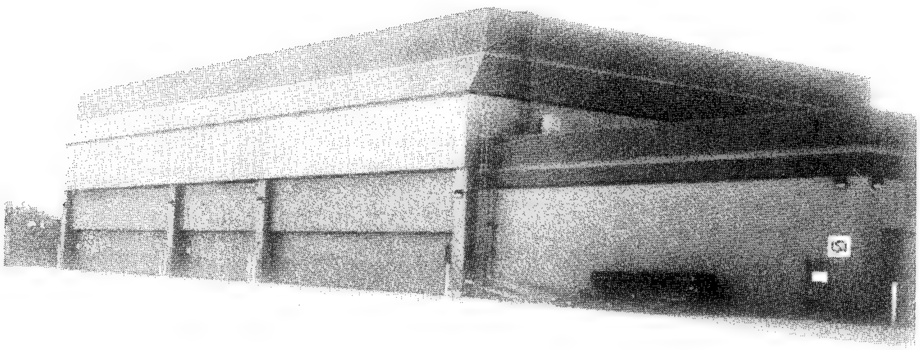
Test procedure

On both days at 4:00 p.m., 30 cm^3 of SF_6 tracer gas was released in proportion to the volume of each space to achieve a uniform target initial concentration of about 1×10^{-9} throughout the building.

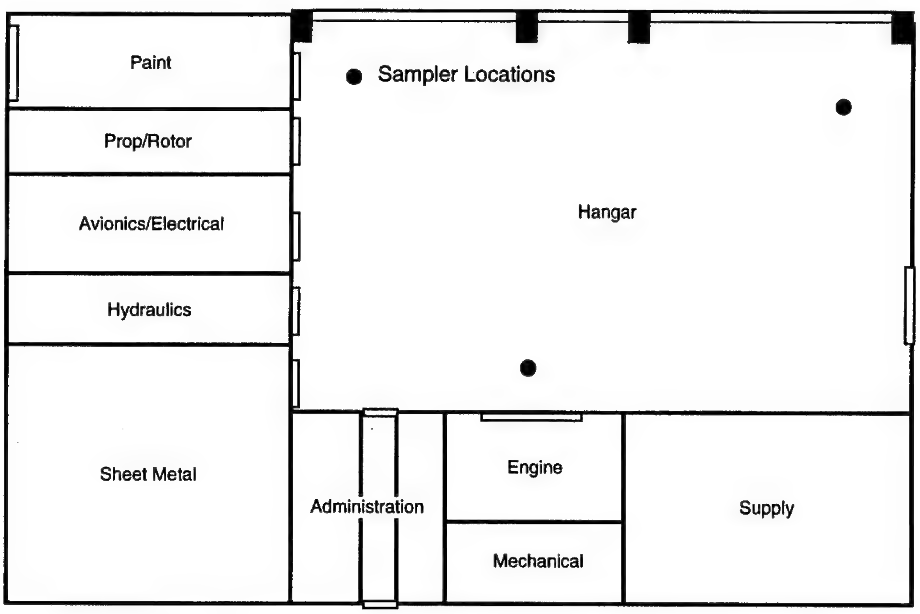
On both days three automated samplers were placed in the hangar space: two at floor level and one near the ceiling. Each sampler was set to take twelve 30-cm^3 air samples, each 20 minutes long, sequentially for an hour, starting when the gas was released. This approach provided both time series and spatial sampling in the building. On both days there was further spatial sampling, with syringe samples taken at four points in the hangar.

Table 16. Tracer gas decay rates at the sampling locations in aviation maintenance and overhaul shop P2050.

Hangar location	*Ventilation off 25 Mar 91*	*Ventilation on 26 Mar 91*
Low, West	0.4	0.2
High, East	0.0	0.4
Low, East	—	0.3



a. Exterior view.



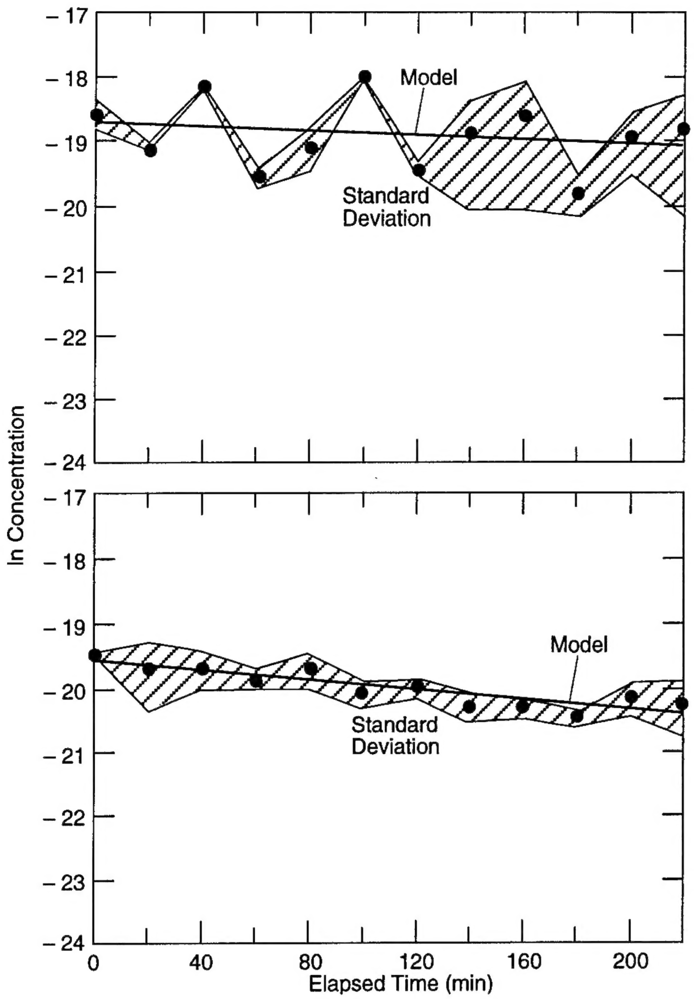
b. Plan (not to scale).

Figure 22. Aviation maintenance and overhaul shop, building P2050.

Test results

On 25 March 1991 only two of the three automated samplers worked. For those two, one near the floor and the other near the roof in the hangar, the average tracer gas decay rate, based on the average of all concentrations, for the hangar was 0.1 h^{-1} while the fans were turned off (Fig. 23a). The initial uniformity of the tracer gas concentration among the hand sampling points in the hangar had an initial coefficient of variation less than 1%. Subsequent time series samples represented too few data per time step for a meaningful calculation of coefficient of variation.

On 26 March 1991 the average tracer gas decay rate, based on the average of all concentrations, for the hangar was 0.2 h^{-1} while the fans were turned on (Fig. 23b). The initial uniformity of the tracer gas concentration among the hand sampling points in the hangar had an initial coefficient of variation of about 13%. Within each shop there was no test for uniform mixing. Table 16 reports the tracer gas decay rate at each sampler. Subsequent coefficients of



a. 25 March 1991.

b. 26 march 1991.

Figure 23. Logarithm of the mean of the data and the regression model of tracer gas concentrations in the aviation maintenance and overhaul shop, building P2050.

variation were between 2 and 50%, based on three data per time-series step.

On both days, the measured tracer gas decay rates were well below the default ASHRAE 62-1989 standard minimum air change rate of 5.4 h^{-1} for this kind of building.

Test analysis

The agreement of just two time series of data in Figure 23a suggests a slight cyclical variation because of wind. The closer agreement of the three time series of data in Figure 23b shows that the tracer gas decay rate was driven primarily by the mechanical ventilation system. The temperatures during these measurement periods were essentially steady.

The confidence intervals depicted in Table 17 show that we would not choose a different regression line through the data depicted in Figure 23 over the period of measurement, and hence we would not choose different average tracer gas decay rates for those periods. However, the confidence intervals for the concentrations at any given time are substantial.

Table 17. Confidence intervals for the average tracer gas decay rate and tracer gas concentration for each of two days in the aviation maintenance and overhaul shop P2050.

	Percent of tracer gas decay rate	*Percent of mean concentration*
25 Mar 91	4	124
26 Mar 91	1	70

DISCUSSION

Single-zone idealization is a difficult goal

The goal of measuring air exchange rate with the single-zone tracer gas decay technique is to achieve a uniform tracer gas concentration in the building

zone. How the tracer gas is injected and mixed, and the building configuration, affect the success of the measurement.

Building configurations

Some of the buildings studied comprised many rooms. In those cases it was not practical to keep all doors open. The HVAC fan system could mix and recirculate the gas; however, such systems are seldom properly balanced, and therefore are not likely to uniformly concentrate the tracer gas. In the large open spaces in maintenance buildings, the junior enlisted club, or the bowling alley, natural convection did not effectively and uniformly mix the tracer gas.

Tracer gas mixing effectiveness

To gauge mixing effectiveness, we can look at two indicators of successful single-zone emulation: variation in tracer gas concentration and variation in tracer gas decay rate at each sampling location. If all concentrations within the zone remain essentially equal, then we know that it is behaving as a single entity. If the concentration drops at a given location, that indicates that indoor air is being replaced with outdoor air at that location.

We might be satisfied if, despite a lack of consistency in tracer gas concentration from point to point, at least the tracer gas decay rate at each location was essentially equal. This would mean that, although some areas represented short circuits for outdoor air replacing indoor air, the building as a whole was performing uniformly.

Table 18. Summary of coefficients of variation for the buildings tested.

Building	*Coefficient of variation (%) for* *Tracer gas concentration*	*Tracer gas decay rate*
Laboratory addition*	20	27
Administrative	21	45
	27	36
Barracks*	10	187
	70	96
Army hospital—operating*	9–35	22
Army hospital—delivery*	37	45
Army hospital—nursery*	12–72	34
Bowling alley	50–80	14
Junior Enlisted Club	60	87
DEH shop	60	97
Unit motor shop*	11–85	770
	18–44	54
Aviation shop	1–76	184
	2–49	35

* The marked buildings represent independent spaces that were designed to have similar tracer gas decay rates.

The coefficients of variation shown in Table 18 indicate that neither tracer gas concentrations nor local tracer gas decay rates were behaving in unison for most of the buildings measured. Does this mean that the results are valueless? Not necessarily. In many cases the data allowed us to observe a central tendency for a consistent air leakage rate, despite the spatial variation.

The buildings that provided a large open space, starting with the bowling alley and continuing with those below it in Table 18, did not demonstrate better coefficients of variation of tracer gas concentration than those that had multiple zones that were idealized as a single zone (upper part of Table 18). Furthermore, the means of tracer gas mixing, using the building air handling system versus natural convection, did not explain the differences.

Effect on accuracy

E741 suggests that 10% variation in concentration within a zone is an attainable goal. When a number of other accuracy conditions are met, then it should be possible to determine *A* (air change rate) within 10%. Only a few exceptional cases met this criterion. In most cases, it is only possible to suggest that the zone had a high or low air change rate compared to its design rate.

Air leakage versus mechanical ventilation

Most of the studies reported here characterized the air change rate attributable to a combination of mechanical ventilation and air leakage through the building envelope. A few studies of shops were conducted with no mechanical ventilation in operation, and thus measured air leakage only.

An air leakage study of the CRREL laboratory addition or of the barracks, building 666, would have been difficult because of all the enclosed spaces that would have to be monitored. These spaces would have behaved very differently from the idealized single zone that predicates this type of measurement. In other buildings, we could use the fan system to distribute the tracer gas, and then turn the fan system off to do the measurement.

CONCLUSIONS

Practical benefits

Ventilation measurements

We can determine whether a ventilation system is supplying sufficient or excessive air changes us-

ing the tracer gas concentration decay technique only if we can maintain a uniform tracer gas distribution throughout the building.

Air leakage measurements

We can determine whether air leakage in the building envelope is causing excessive air changes by turning off and closing off the mechanical ventilation system and using the tracer gas concentration decay technique. It is more difficult to distribute tracer gas throughout the building without the fan system recirculating air during the measurement. However, running the fan system may cause bias in the measurement.

In this study of Army buldings, the goal of uniform tracer gas concentration was usually not achieved.

Technical challenges

Single-zone idealization

The goal of measuring air exchange rate with the single-zone tracer gas decay technique is to achieve a uniform tracer gas concentration in the building zone. In this study, the tracer gas injection strategy, the tracer gas mixing strategy and the building configuration only occasionally approximated the ASTM standard of a 10% coefficient of variation.

In large, open-bay buildings, distributing tracer gas by hand and then relying on natural convection for sufficient mixing is not enough to achieve good results with the tracer gas decay technique. A system of fans is apparently necessary. This significantly increases the equipment burden for the investigator.

It is unrealistic to expect multicompartmented buildings to perform as single zones using the simple tracer gas injection and mixing strategies employed here in connection with the tracer gas decay technique. To evaluate these multizone buildings, we must be prepared to use more complex injection techniques and equipment. Practically speaking, this might entail an extensive network of tracer gas injection and air sampling tubing to each compartment in the building.

Ventilation measurements

Before resorting to techniques better suited to multizone buildings, we can use the tracer gas concentration decay technique to get an idea of average tracer gas decay rates attributable to mechanical ventilation and air leakage in a multi-zone building. While the 10% coefficient of variation in tracer gas concentrations from place to place within the building suggested by ASTM E741 is difficult to obtain, we can check for a spatial bias in tracer gas concentrations by comparing a physical mean obtained at a return air plenum for the building with the mean of spatial samples.

We should expect to attain the 10% accuracy in determining average air change rate in a large, single-zone building only with significant air mixing efforts, using the tracer gas decay technique. We should not expect to achieve such accuracy in multizone buildings.

Air leakage measurements

We can expect to do air exchange measurements whereby the exchange is ascribable solely to air leakage only in truly single-zone buildings with reasonably uniform tracer gas concentrations throughout. The use of internal fan circulation in multizone buildings has a slight chance to overcome the problem of uniform concentration. Use of the constant concentration technique described in ASTM E741 could overcome this difficulty, but with the expense of an elaborate tracer gas injection, control and sampling system.

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Air exchange measurements in buildings are important for testing the effectiveness of the ventilation system and for characterizing air leakage in the building envelope when the ventilation is off. This report discusses such measurements in nine Army buildings—administrative, maintenance, barracks, hospital and laboratory buildings—using a tracer gas method that entails releasing a tracer gas in an initial well-mixed concentration and then monitoring its concentration over time. The faster the tracer gas dilutes, the greater is the air change rate. ASTM Standard E741 offers techniques for tracer gas measurements in single-zone enclosures, but most Army buildings are multiple-zone enclosures. This study, looking at whether such buildings could approximate single-zone enclosures for tracer gas measurements, found that this is difficult. In addition, a number of buildings were detected in which the mechanical ventilation system was working at a fraction of design capacity.

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